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(54) **F-K filtering of multiple reflections from a seismic section**

(57) Multiple reflections are filtered from seismograms by transforming the seismograms at 34, 35 into an f-k array representing amplitude as a function of frequency and wave number. The inverse of the f-k transform of the multiple reflections is generated at 18-31 and the f-k array of the seismograms is filtered at 32, 33 by weighting all samples with the inverse of the f-k transform of the multiple reflections.

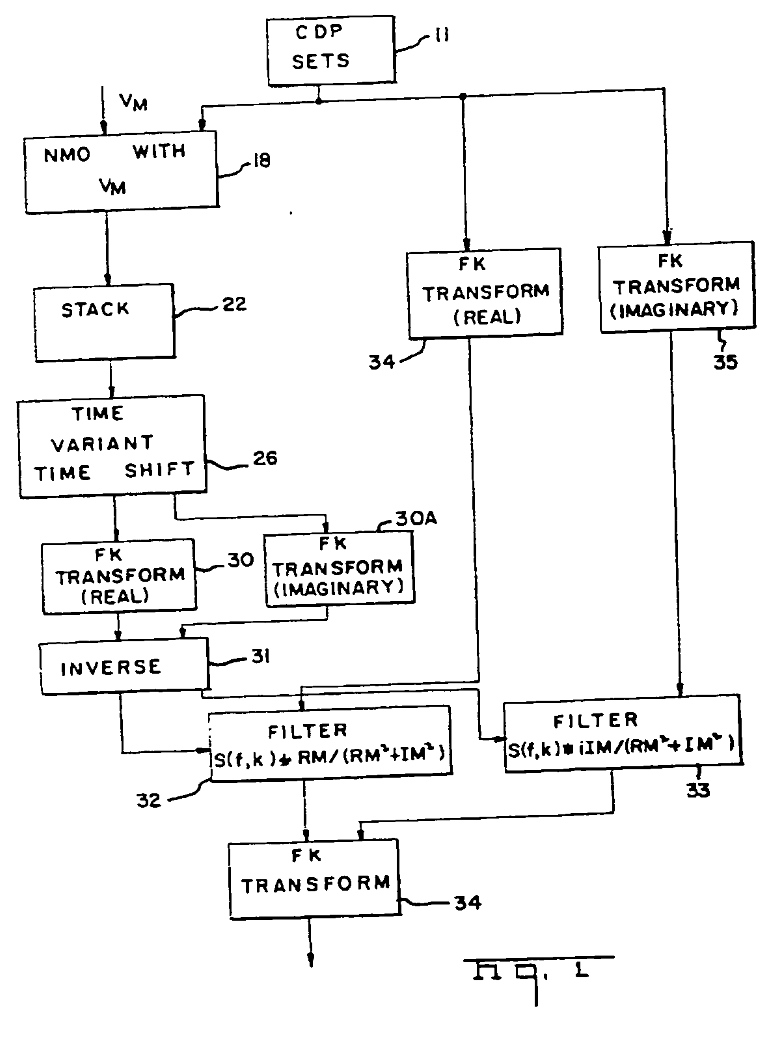

Fig. 1

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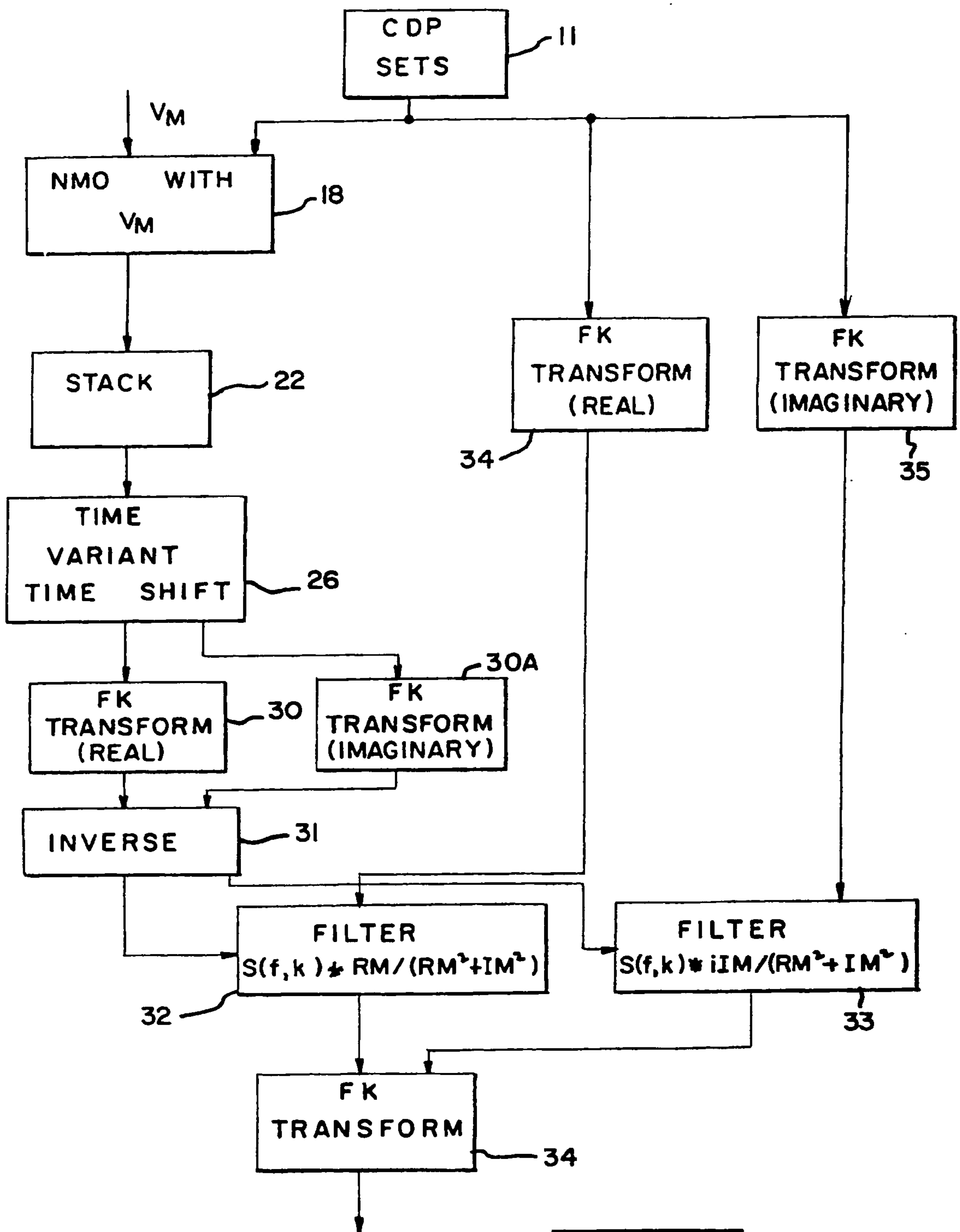
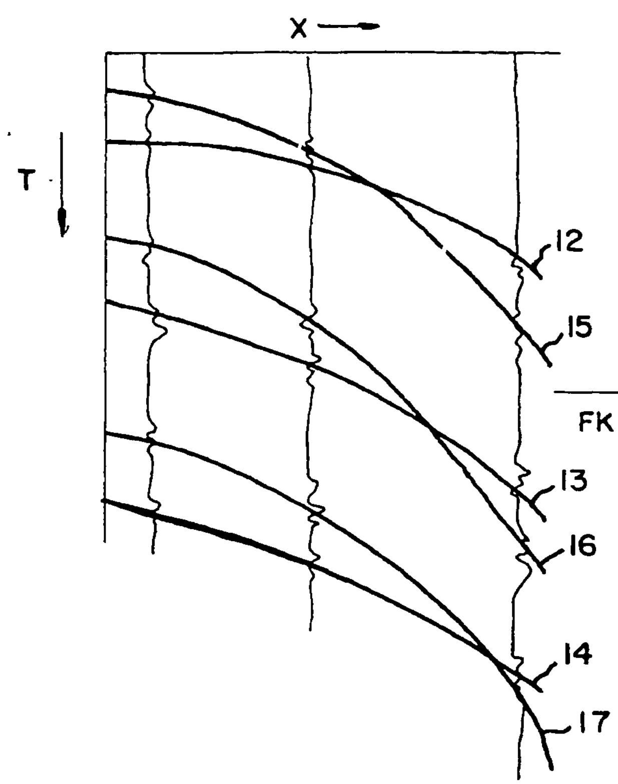



Fig. 1



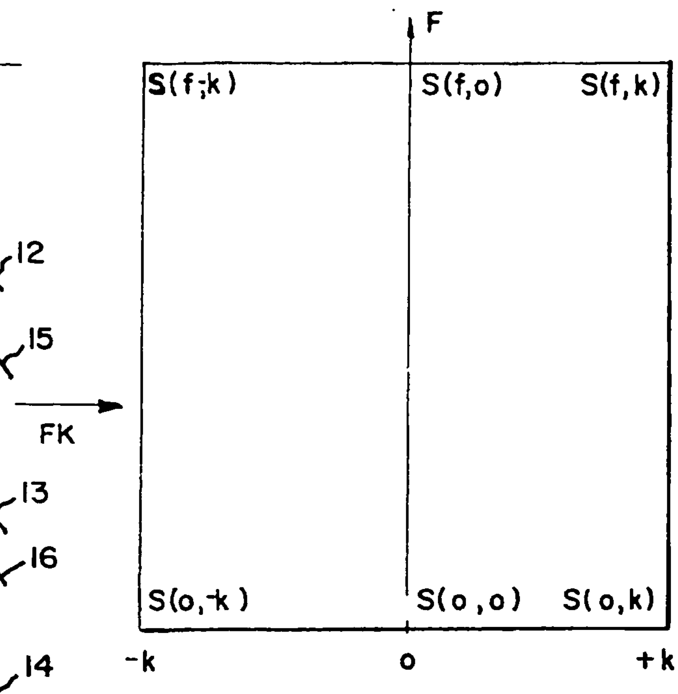




Fig. 2

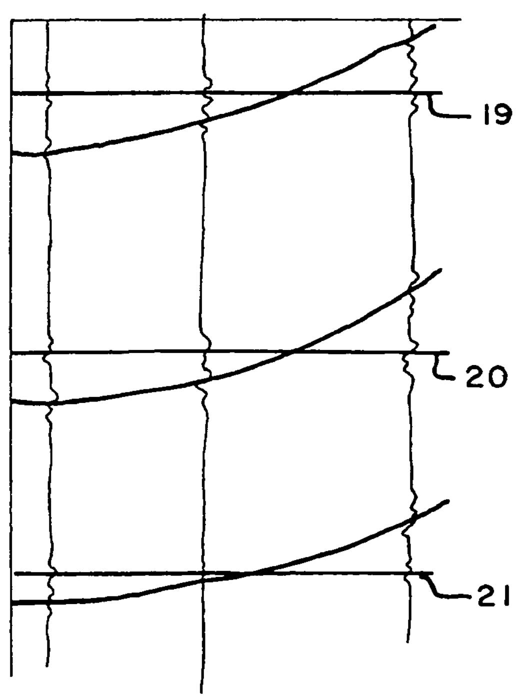



Fig. 3

Fig. 4

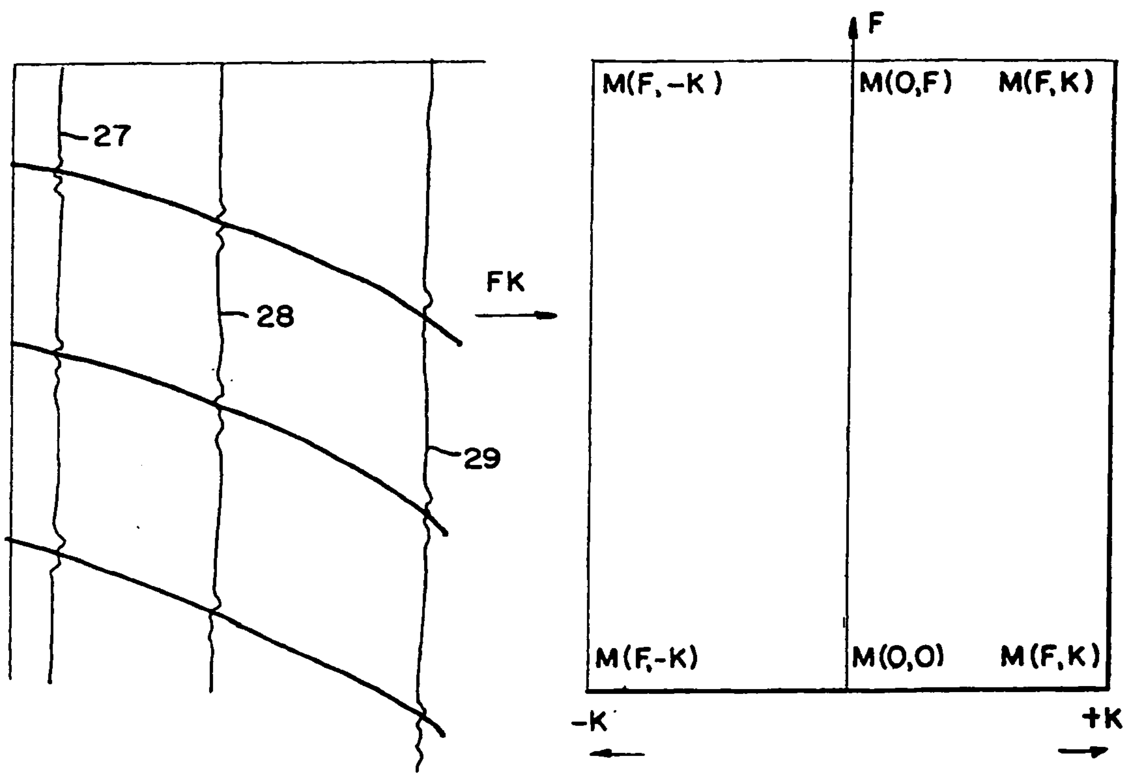



Fig. 5

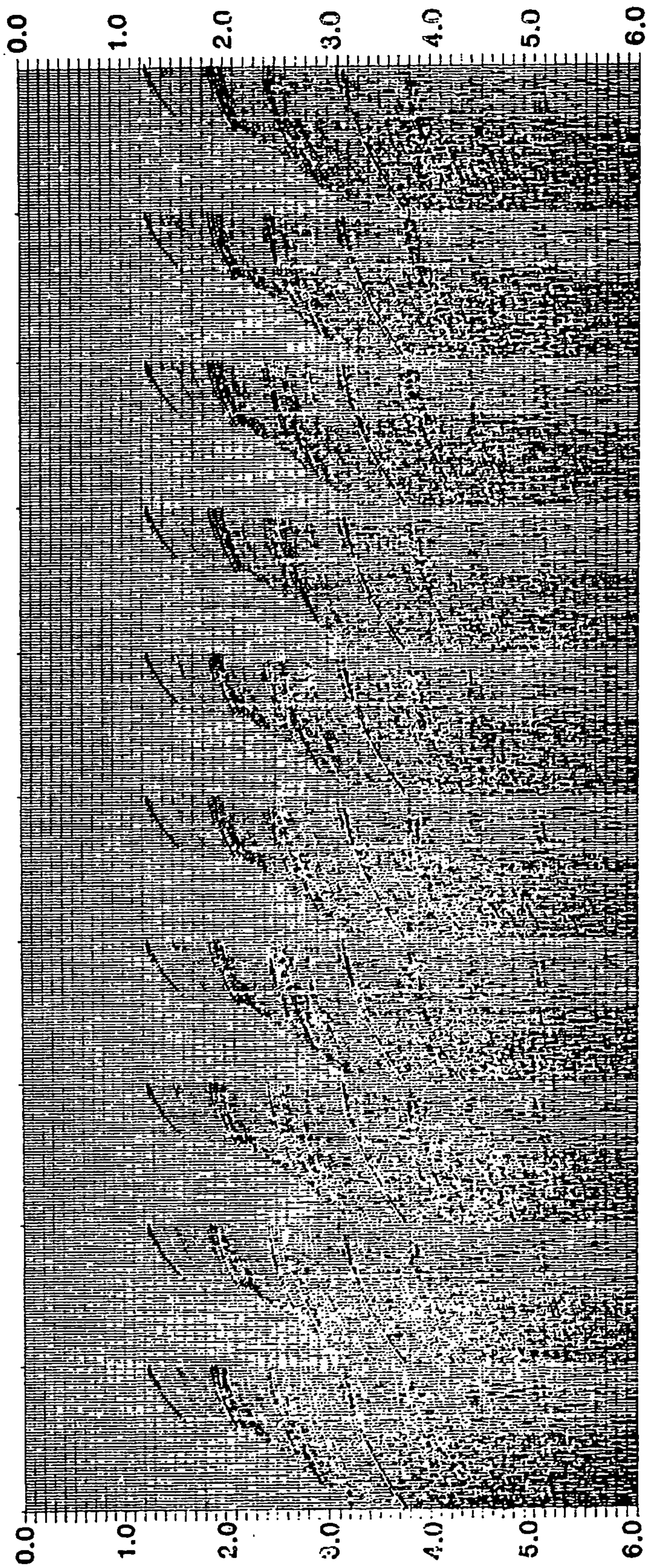



Fig. 6

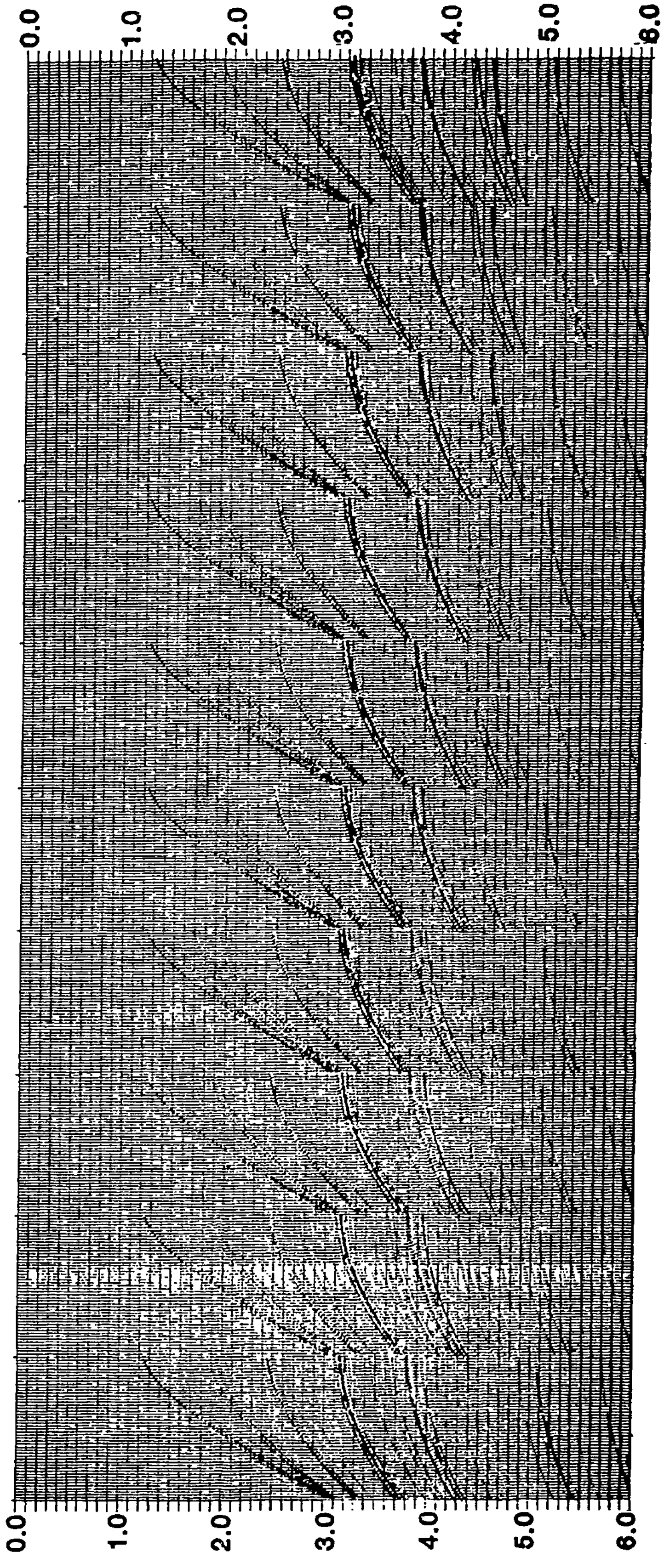



Fig. 7

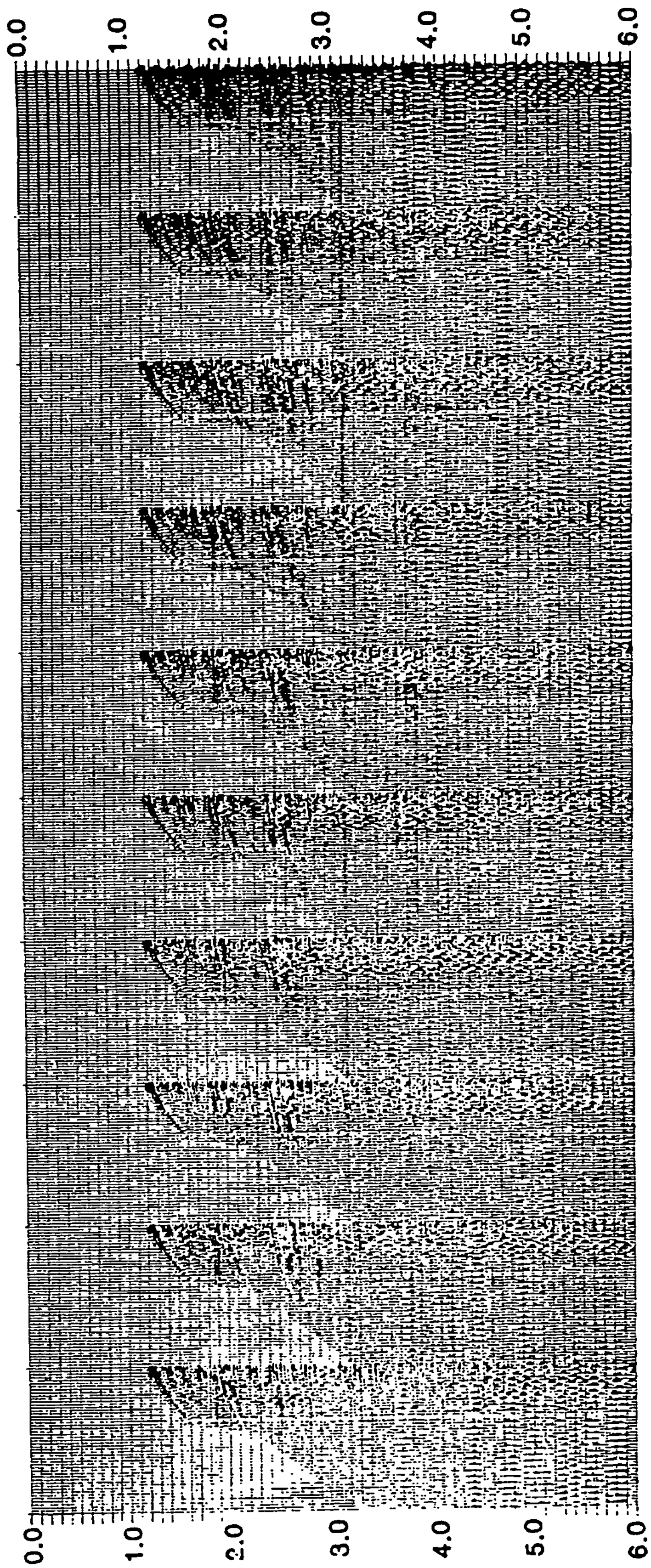



Fig. 6

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Fig. 9

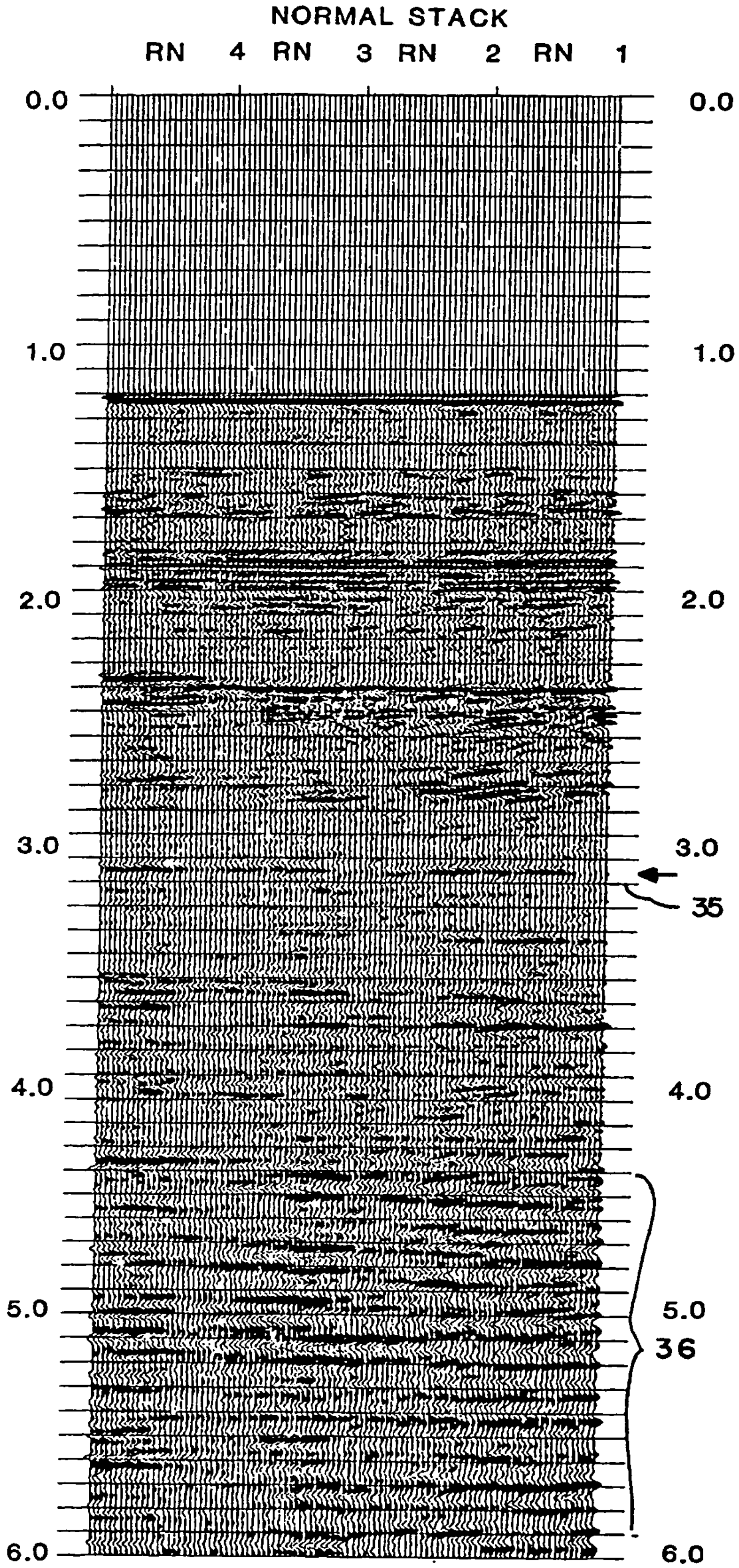
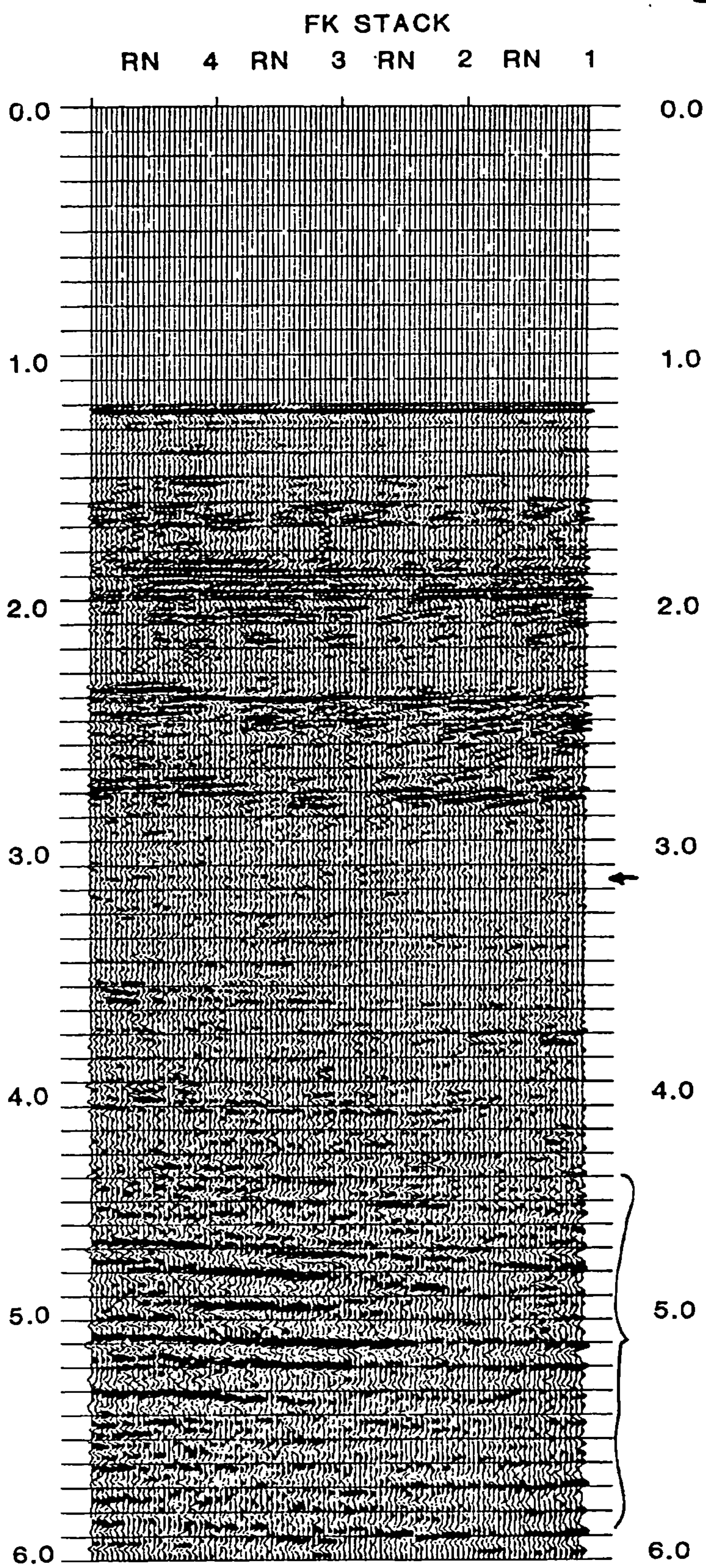


Fig. 10



SPECIFICATION

**F-K filtering of multiple reflections from a seismic section**

This invention relates to geophysical exploration and more particularly to the filtering of multiple reflections from a seismic section.

A seismic section is a set of seismograms which depicts the subsurface layering of a section of the earth. Before an array of seismic samples can be converted into a seismic section which can be interpreted by the geophysicist, the seismograms must be procesed to remove noise. One of the most frequently occurring types of noise arises from multiple reflections of the seismic energy between reflecting layers in the earth.

Various processes have been devised for suppressing multiple reflections. In one such process, multiple seismic coverage is obtained and stacked to suppress the multiple reflections. Various names have been given to the general process of obtaining multiple seismic coverage, e.g., common depth point techniques, common reflection point techniques, and roll-along techniques. All these techniques involve the general principle of recording multiple seismic data from the same reflection point in the subsurface by employing variable horizontal spacing between a seismic source and seismic detector. These techniques are applicable to both marine and land seismic work. A description of such techniques is given by Lorenz Shock in an article entitled "Roll-Along and Drop-Along Seismic Techniques", published in GEOPHYSICS, Vol. XXVIII, No. 5, Part II, pp. 831-841, October, 1963. The data are corrected for normal moveout and statics and are then stacked.

Common depth point seismic techniques are generally credited with producing better seismic data than those techniques which produced single-fold seismic data. In stacking the common depth point seismic data, the primary reflections are essentially in phase and thus are added whereas the distortions such as multiple reflections are out of phase and tend to be cancelled. Thus the multiple reflections are suppressed and the primary reflections are enhanced.

The seismic arrays produced by these methods are generally X-T arrays in which the amplitude of the seismic reflections is plotted as a function of record time (T) and distance (X). These arrays may be transformed into f-k arrays which represent amplitude as a function of frequency and wave number.

In our co-pending patent application No. 8125268 (Mobil Case F-0343) we have described a method for obtaining an improved representation of the subsurface layering by filtering the f-k transform. The filtering is carried out on digitized samples by weighting the samples in closed regions of frequency and wave number with a weighting dependent upon the signal and the noise.

We have now found that f-k filtering may be used to suppress multiples by weighting all the samples in the f-k array with the inverse of the f-k transform of the multiple reflections.

One way of carrying out the invention is to make a normal moveout correction with the apparent velocity of the multiple reflections. This aligns the multiple reflections in the CDP set. By stacking the CDP set after correction for normal moveout, an estimate is obtained of the multiple reflections. This estimate is successively time shifted by varying times to produce seismograms representing a CDP set of the multiple reflections. The multiple reflection CDP set is converted into an f-k array and the inverse of this array is obtained. This is an array of samples which are inversely proportional to the amplitude of the multiple reflections as a function of frequency and wave number.

The seismic section from which multiple reflections are to be filtered is also converted into an f-k array. This f-k array is filtered by weighting all samples in it by the corresponding samples in the inverse multiple reflection f-k array. In this manner, multiple reflections are suppressed. When the filtered f-k array is converted into a normal X-T array, an enhanced representation of the earth's formations without multiple reflections is obtained.

Further features and advantages of the invention are disclosed below with reference to the drawings in which:

*Figure 1* is a flow sheet depicting the filtering process;

*Figure 2* depicts a set of CDP seismograms, and the f-k transform of that set;

*Figure 3* depicts the CDP set of Figure 1 after correction for normal moveout with the apparent velocity of the multiple reflections;

*Figure 4* depicts an estimate of multiple reflections obtained by stacking the CDP set of Figure 3;

*Figure 5* depicts a set representing the multiple reflections which has been obtained by successively time shifting the estimate of Figure 4;

*Figure 6* is an example of sets of CDP seismograms;

*Figure 7* shows sets of seismograms representing the multiple reflections in the sets of Figure 6;

*Figure 8* depicts the sets of Figure 6 after multiple reflections have been filtered out in accordance with the present filtering process;

*Figure 9* is an example of a field section which has been processed and stacked with standard procedures; and

*Figure 10* depicts the same seismograms after the f-k multiple reflection filtering and stacking of the present filtering process.

The filtering process shown in Figure 1 operates on sets of common depth point seismograms 11. Such CDP sets are depicted in Figure 2, wherein the X direction depicts distance along a line of exploration and the T direction depicts time after the pulse of seismic energy producing the seismograms. In accordance with CDP techniques, the seismograms in each set contain reflections of seismic energy from the same reflecting points. The reflections from subsurface interfaces occur in the sets along approximately hyperbolic arcs such as 12, 13 and 14 in Figure 2. The time of a reflection in any set is given by the well known expression:

$$T^2 = T_0^2 + X^2/V^2$$

where $T_0$ is the time of the reflection at the zero offset trace, X is the horizontal distance between source and detector, and V is the acoustic velocity characteristic of the earth. The multiple reflections line up along different hyperbolic arcs such as 15, 16 and 17 in Figure 2. Such a seismic set is generated in the field and stored on magnetic tape or in a digital computer as an array of seismic samples representing the amplitude of the seismic reflections as a function of time T and distance X along the line of exploration. The samples in such an array are designated S(X,T). Fourier transforms which convert such an array into an array of amplitude as a function of frequency and wave number are known. Such an f-k array is shown at the right side of Figure 2. The digital samples are denoted S(f,k).

As a first step toward obtaining seismograms representing only multiple reflections, the CDP sets 11 are corrected for normal moveout with the apparent velocity $V_m$ of the multiple reflections. This step is indicated at 18 in Figure 1. It produces the seismic set which is depicted in Figure 3. In this set, the multiple reflections have been aligned so that they appear on the straight lines 19, 20 and 21. When such a set is stacked, an estimate of the multiple reflections is obtained. The step of stacking is indicated at 22 in Figure 1.

The resulting estimate of the multiple reflections is shown in Figure 4 where the stacked seismogram has the multiple reflections 23, 24 and 25. This estimate is converted into a CDP set representing the multiple reflections. The time variant time shift indicated at 26 in Figure 1 performs this operation. This is merely a time shifting operation which is the reverse of the normal moveout operation indicated at 18. That is, the apparent multiple velocity is used to determine the time shift to be successively applied to the estimate of Figure 4 to produce the set representing multiple reflections in Figure 5. Figure 5 depicts the estimates 27, 28 and 29, each with successive time shifts, but of course there will be many more seismograms in the typical CDP set.

Figure 5 also depicts the f-k transform of the set representing the multiple reflections. The set representing multiple reflections at the left in Figure 5 is represented by an array of digital samples representing amplitude as a function of time and distance. The digital samples in such an array are designated M(X,T) where each digital sample represents an amplitude for a particular value of X and T. The right hand side of Figure 5 depicts an array of digital sample for each frequency and wave number value in the array. The digital samples are designated M(f,k) where each digital samples represents the amplitude for a particular value of frequency and wave number.

The step of performing the f-k transform on the set representing multiples is indicated at 30 and 30A in Figure 1. This step can be carried out by many conventional Fourier transforms, but the Cooley-Tukey transform described in Cooley, J.W.; Tukey, J.W., "An Algorithm for Machine Calculation of Complex Fourier Series", *Mathematical Computation*, Vol. 19, 1965, pp. 297-301 is particularly suitable for use. The adaptation of the transform for use in seismic processing is more fully described in our co-pending application referenced above and incorporated by reference. That application also describes in more detail the transform into a real part, indicated at 30, and the transform into an imaginary part, indicated at 30A.

In accordance with the present invention, the inverse of the array M(f,k) representing multiples, is obtained in order to determine the weights of the filter which is to be applied. This step of generating the inverse is indicated at 31 in Figure 1. An inverse operation performed on an f-k array is carried out by division. That is, the weights, W(f,k) of the filter are the inverse of the multiple reflection section. Stated in another way,

$$W(f,k) = 1/M(f,k) = 1/(RM + iIM)$$

In the foregoing, RM represents the real part of the weighting function and iIm represents the imaginary part. In co-pending application No. 8125268 (Mobil Case F-0343) the multiples are removed by a reject filter which operates only on the absolute value of the transform of the seismic section. The filter of the present process operates on the complex real and imaginary parts of the f-k transform of the seismic section. The operation is simplified by multiplying both the numerator and the denominator by RM - iIM. This produces:

$$W(f,k) = RM/(RM^2 + IM^2) - iIM/(RM^2 + IM^2)$$

The foregoing consists of two parts. One contains the coefficients for filtering the real part of the seismic section. The other contains the coefficient for filtering the imaginary part of the seismic section. The real coefficients are applied to the filter 32. The imaginary coefficients are applied to the filter 33.

The seismic section to be filtered is converted into an f-k array by the real f-k transform 34 and the imaginary f-k transform 35. Again, these f-k transforms may be performed in accordance with the procedure described in co-pending application No. 8125268 (Mobil Case F-0343). The real part of the array S(f,k) is applied to the filter 32 and the imaginary part is applied to the filter 33. The filters 32 and 33 weight each of the samples in the array S(f,k) by a factor which is inversely proportional to the amplitude of the corresponding sample in the f-k transform of the multiple reflections. In implementing the filtering in a digital computer, the simplest procedure is to multiply each filter coefficient, from the inverse multiple reflection f-k array, by the corresponding sample in the seismic section f-k array. Digital filtering techniques are well known. The filtering has the effect of suppressing multiple

reflections. The filtered arrays are transformed back into normal X-T arrays by th step indicated at step 34. This produces a section having enhanced representation of the earth's formation without the multiple reflections.

Examples of the operation of the present invention are shown in the seismograms of Figures 6-10. Figure 6 depicts field seismograms in ten CDP sets. This corresponds with the idealized set shown in Figure 2. After processing by the steps 18, 22 and 26 of Figure 1, these field seismograms have the appearance of Figure 7. Figure 7 shows sets representing only multiple reflections. These sets are converted into an f-k array by the steps 30 and 30A of Figure 1 and the weighting coefficients of the filter are determined by the inverse operation depicted at 31 in Figure 1.

Figure 8 shows seismic sets which have been transformed into an f-k array, filtered by the steps 32 and 33 of Figure 1 and then transformed back into an X-T array. Good multiple suppression has been obtained.

Figures 9 and 10 are further examples of the effectiveness of the present invention. Figure 9 shows a seismic section which has been stacked after standard processing. Note the strong multiple reflection indicated at 35, approximately 3.15 seconds record time. Also there is severe ringing caused by multiple reflections in the portion of the record indicated at 36, approximately 4.4 through 6.0 seconds of record time.

Figure 10 is the same seismic section which has been processed and stacked by the same processing except that the f-k multiple filtering of the present invention has been applied. Note that the multiple reflection at 3.15 seconds has been effectively suppressed. Also, the ringing between 4.4 and 6.0 seconds has been greatly improved.

CLAIMS

1. A method of filtering multiple reflections from seismograms representing the earth's formations comprising:

transforming seismograms representing the amplitude of seismic reflections as a function of time and distance along a line of exploration into an f-k array representing the amplitude of the reflections as a function of frequency and wave number;

generating the inverse of the f-k transform of the multiple reflections;

filtering the f-k array by weighting all the samples in the array with the inverse of the multiple reflections; and

generating from the filtered array a seismic record having an enhanced representation of the formations with suppression of the multiple reflections.

2. A method according to claim 1 in which the inverse of the f-k transform of the multiple reflections is generated by:

correcting the seismograms for normal moveout with the apparent velocity of the multiple reflections so as to align the multiple reflections;

transforming the corrected seismograms with aligned multiple refl ctions into an f-k array; and

determining the inverse of the f-k array.

3. A method according to claim 2 in which the normal moveout correction is made by time shifting common depth point sets with the apparent velocity of the multiple reflections to align the multiple reflections, and the transforming is made by stacking the normal moveout corrected common depth point sets to produce an estimate of the multiple reflections, successively time shifting the estimate of multiple reflections by varying times to produce a set representing the multiple reflections, and transforming each set into an f-k array.

4. A method according to any of claims 1 to 3 in which the filtering is performed by weighting each sample in the f-k array by a factor which is inversely proportional to the amplitude of the corresponding sample in the f-k transform of the multiple reflections.

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